Indirect limits on SUSY Rp violating couplings lambda and lambda'

F. Ledroit, G. Sajot

GDR–S–008

Indirect limits on SUSY R_p violating couplings λ and λ'.

F. Ledroit, G. Sajot
ISN Grenoble

May 6, 1998

Abstract

We review and update as many as possible indirect limits on SUSY R_p violating couplings λ and λ'. We consider about 25 experimental measurements and compare them to their expectation value in the standard model. We find more stringent limits on almost all of the parameters.

Introduction

In the supersymmetric extension of the standard model (SM), the most general superpotential contains terms allowing the violation of R-parity quantum number $R_p = (-1)^{(3B+L+2S)}$:

$$\mathcal{W} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

R_p violation leads to measurable effects, such as lepton universality violation for instance. The non observation of these effects sets limits on the size of λ, λ' and/or λ'' couplings. We will not consider here the baryon number non conserving terms λ'', nor limits on $\lambda^{(\prime)}\lambda^{(\prime)}$ products.

A first type of processes which can be used corresponds to processes that are allowed in the SM, for which R_p violating graphs contribute at the tree level. Weak decays of leptons and mesons, $\nu_\mu e$ scattering, ν_μ deep inelastic scattering (DIS), atomic parity violation and asymmetries belong to this category. Usually, these processes are exactly calculable in the SM, or else the factors having non negligible theoretical uncertainties cancel in well chosen ratios.

Other processes, occuring only through loop or box diagrams, or even forbidden in the SM, such as $B^0\bar{B}^0$ mixing or $K^- \to \pi^-\nu\bar{\nu}$ for instance, can be used as well.

In this note, we derive limits on λ and λ' couplings using the methods and calculations of references [1]–[4] and recent experimental input, coming mainly from the 1997 (electronic) edition of the Particle Data Group (PDG) review [5] and from the LEP Electroweak Working Group and SLD Heavy Flavour Working Group report [6].

1 Tree level processes

Following Barger et al.[1], we define a positive and dimensionless coupling:

$$r_{ijk}(\tilde{f}) = \frac{M_W^2}{g^2} \times \frac{|\lambda_{ijk}|^2}{m_{\tilde{f}}^2}$$

Using $\dfrac{M_W^2}{g^2} = \dfrac{\sqrt{2}}{8G_F}$ and $G_F = 1.1664 \times 10^{-5}$, one obtains:

$$|\lambda_{ijk}| = 0.8123\sqrt{r_{ijk}}(\tfrac{m_{\tilde{f}}(\mathrm{GeV})}{100}).$$

This expression, and the equivalent relation between r'_{ijk} and λ'_{ijk}, will be used in the following to re-compute the limits on $|\lambda|$ ($|\lambda'|$) from limits on r_{ijk} (r'_{ijk}). This is done by first assuming one single non vanishing λ or λ' at a time, and then by maximizing r_{ijk} (r'_{ijk}) with respect to the experimental error on the considered physical quantity. Following Barger et al.[1], we call limit at 1σ (at 2σ) the number obtained by comparing the experimental measurement to its value in the SM, after adding or subtracting 1σ (2σ) to the experimentally measured value.

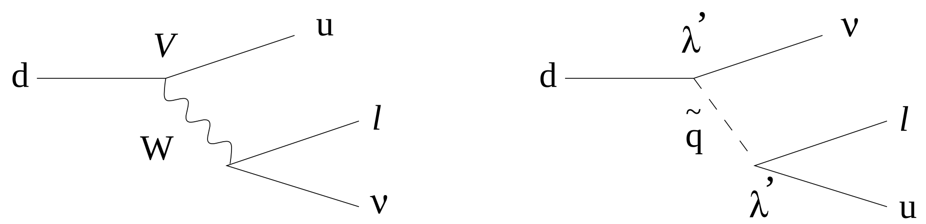

Figure 1: Nuclear β decay and the R_p violating contribution to the same effective CKM matrix element.

We also compute r_{ijk} (r'_{ijk}) and their error in order to combine, in section 1.4, several measurements constraining the same λ_{ijk} (λ'_{ijk}).

In all cases, we assume that no other kind of 'new physics' is present, that would possibly give rise to compensating effects.

1.1 Decays (charged currents)

Precise measurements of partial decay widths or branching ratios combined by the PDG [5] are used here; there are usually two numbers for a given quantity: the output of a global fit, and the average of the quantity alone. We systematically take the latter, in order not to weaken possible effects of R_p violating interactions over all the measured decays of a given particle.

1.1.1 Charged current universality

In the SM at parton level, W bosons decaying to leptonic and hadronic final states are expected to have same strength couplings, modulo Cabbibo-Kobayashi-Maskawa (CKM) matrix elements. $|V_{ud}|$ is then given by comparing nuclear β decay to muon decay: $|V_{ud}|^2 \propto \Gamma(d \to u e^- \bar{\nu}_e)/\Gamma(\mu \to \nu_\mu e^- \bar{\nu}_e)$. In the same way, $|V_{us}|$ is measured in $K^+ \to \pi^0 e^+ \nu_e$ decays and $|V_{ub}|$ in charmless B decays. R_p violating couplings spoil this universality. Processes with graphs of the type shown in figure 1 give:

$$|V_{ud_j}^{exp}|^2 = \frac{|V_{ud_j}^{SM} + r'_{1jk}|^2}{|1 + r_{12k}|^2} \simeq \frac{|V_{ud_j}^{SM}|^2 (1 + 2r'_{1jk}/|V_{ud_j}^{SM}|)}{|1 + r_{12k}|^2}$$

Assuming unitarity of the CKM matrix: $\sum_{j=1,3} |V^{SM}_{ud_j}|^2 = 1$,

$$\sum_{j=1,3} |V^{exp}_{ud_j}|^2 \simeq \frac{1 + 2(|V^{SM}_{ud}|r'_{11k} + |V^{SM}_{us}|r'_{12k} + |V^{SM}_{ub}|r'_{13k})}{|1 + r_{12k}|^2}$$

From [5]: $|V^{exp}_{ud}| = 0.9740 \pm 0.0010$, $|V^{exp}_{us}| = 0.2196 \pm 0.0023$

$|V^{exp}_{ub}/V^{exp}_{cb}| = 0.08 \pm 0.02$, $|V^{exp}_{cb}| = 0.0395 \pm 0.0017$

we derive $|V^{exp}_{ub}| = 0.0032 \pm 0.0008 \Rightarrow \sum_j |V^{exp}_{ud_j}|^2 = 0.9969 \pm 0.0022$

- $r_{12k} = 1/\sqrt{\sum_j |V^{exp}_{ud_j}|^2} - 1 = (1.55 \pm 1.11) \times 10^{-3}$;
  r_{12k} is maximum for $\sum_j |V^{exp}_{ud_j}|^2$ minimum.
  $\sum_j |V^{exp}_{ud_j}|^2 - 1\sigma = 0.9947$, $\sum_j |V^{exp}_{ud_j}|^2 - 2\sigma = 0.9925$
  $\Rightarrow \boxed{|\lambda_{12k}| < {\scriptstyle 0.04\,(1\sigma) \atop \scriptstyle 0.05\,(2\sigma)} \times (m(\tilde{e}^k_R)/100)}$

- Taking $V^{SM}_{ud_j} = V^{exp}_{ud_j}$:
  $$\left\{ \begin{array}{l} r'_{11k} \simeq (\sum_j |V^{exp}_{ud_j}|^2 - 1)/(2|V^{SM}_{ud}|) = (-1.59 \pm 1.13) \times 10^{-3} \\ r'_{12k} \simeq (\sum_j |V^{exp}_{ud_j}|^2 - 1)/(2|V^{SM}_{us}|) = (-7.1 \pm 5.0) \times 10^{-3} \\ r'_{13k} \simeq (\sum_j |V^{exp}_{ud_j}|^2 - 1)/(2|V^{SM}_{ub}|) = -0.48 \pm 0.36 \end{array} \right. ;$$
  r'_{11k}, r'_{12k} and r'_{13k} are maximum for $\sum_j |V^{exp}_{ud_j}|^2$ maximum.
  $\sum_j |V^{exp}_{ud_j}|^2 + 1\sigma = 0.9991$: no limit at 1σ, $\sum_j |V^{exp}_{ud_j}|^2 + 2\sigma = 1.0013$
  $\Rightarrow \boxed{|\lambda'_{11k}| < 0.02 \times (m(\tilde{d}^k_R)/100) \ \ (2\sigma)}$
  $\boxed{|\lambda'_{12k}| < 0.04 \times (m(\tilde{d}^k_R)/100) \ \ (2\sigma)}$
  $\boxed{|\lambda'_{13k}| < 0.37 \times (m(\tilde{d}^k_R)/100) \ \ (2\sigma)}$

Limits on λ'_{11k}, λ'_{12k} and λ'_{13k} are less stringent for higher families due to the fact that the corresponding CKM matrix elements become increasingly smaller.

1.1.2 e-μ-τ universality

In the same way, considering now the leptonic decays of the W, the existence of R_p violating couplings destroys their leptonic universality (see figure 2).

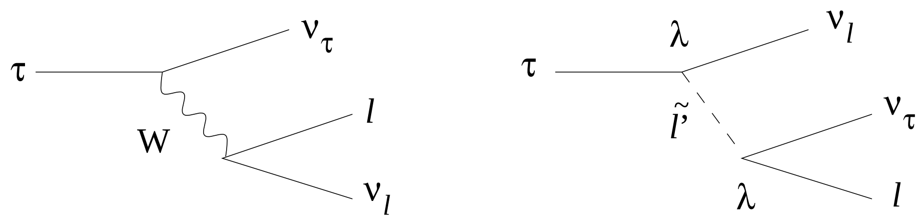

Figure 2: τ decays.

<u>R_τ</u> $\quad R_\tau = \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu}) = Br(\tau \to e\nu\bar{\nu})/Br(\tau \to \mu\nu\bar{\nu})$.
$R_\tau^{exp}/R_\tau^{SM} = \dfrac{|1+r_{13k}|^2}{|1+r_{23k}|^2}$.

In the SM, with radiative corrections [7]:

$$\Gamma(L \to l\nu\bar{\nu}(\gamma)) = \frac{G_F^2 m_L^5}{192\pi^3} f(\frac{m_l^2}{m_L^2})(1+\frac{3}{5}\frac{m_L^2}{m_W^2}-2\frac{m_l^2}{m_W^2})(1+\frac{\alpha(m_L)}{2\pi}(\frac{25}{4}-\pi^2)) \quad (1)$$

$f(y) = 1 - 8y + 8y^3 - y^4 - 12y^2 \ln y \Rightarrow R_\tau^{SM} = 1.0282$.
From $Br^{exp}(\tau \to e\nu\bar{\nu}) = (17.80 \pm 0.08)\%$ and $Br^{exp}(\tau \to \mu\nu\bar{\nu}) = (17.30 \pm 0.10)\%$ [5], we derive $R_\tau^{exp} = 1.0289 \pm 0.0075$ and therefore $R_\tau^{exp}/R_\tau^{SM} = 1.0007 \pm 0.0073$.

- $r_{13k} = \sqrt{R_\tau^{exp}/R_\tau^{SM}} - 1 = (0.34 \pm 3.65) \times 10^{-3}$;
  $R_\tau^{exp}/R_\tau^{SM} + 1\sigma = 1.008$, $R_\tau^{exp}/R_\tau^{SM} + 2\sigma = 1.015$
  $\Rightarrow \boxed{|\lambda_{13k}| < {}^{0.05\,(1\sigma)}_{0.07\,(2\sigma)} \times (m(\tilde{e}_R^k)/100)}$
- $r_{23k} = \sqrt{R_\tau^{SM}/R_\tau^{exp}} - 1 = (-0.34 \pm 3.64) \times 10^{-3}$;
  $R_\tau^{SM}/R_\tau^{exp} + 1\sigma = 1.007$, $R_\tau^{SM}/R_\tau^{exp} + 2\sigma = 1.014$
  $\Rightarrow \boxed{|\lambda_{23k}| < {}^{0.05\,(1\sigma)}_{0.07\,(2\sigma)} \times (m(\tilde{e}_R^k)/100)}$

R_τ gives about the same sensitivity as charged current universality on λ.

In this case of leptonic decays of the τ, the SM expectations are extremely well known and in fact, it is not necessary to work with the ratio of both channels. Testing them separately allows to evade[1] the assumption of one single λ non zero at a time, at the price of re-introducing some small uncertainties in the SM prediction.

Plugging $m_\tau = 1777^{+0.30}_{-0.27}$ MeV, $\tau_\tau = (290.7 \pm 1.3) \times 10^{-15}$s, $m_W = 80.35 \pm 0.12$ GeV [5], $\alpha(m_\tau) = (136.)^{-1}$ and $\alpha(m_\mu) = (133.3)^{-1}$ in relation (1), one gets

$$\left\{ \begin{array}{l} Br^{SM}(\tau \to e\nu\bar{\nu}) = (17.8114 \pm 0.0797)\% \\ Br^{SM}(\tau \to \mu\nu\bar{\nu}) = (17.3227 \pm 0.0775)\% \end{array} \right. .$$

- $r_{13k} = \sqrt{Br(\tau \to e\nu\bar{\nu})^{exp}/Br(\tau \to e\nu\bar{\nu})^{SM}} - 1;\ Br^{exp}/Br^{SM} + 1\sigma = 1.0055,\ Br^{exp}/Br^{SM} + 2\sigma = 1.0119$

  $\Rightarrow \boxed{|\lambda_{13k}| < \begin{smallmatrix} 0.04\,(1\sigma) \\ 0.06\,(2\sigma) \end{smallmatrix} \times (m(\tilde{e}^k_R)/100)}$

- $r_{23k} = \sqrt{Br(\tau \to \mu\nu\bar{\nu})^{exp}/Br(\tau \to \mu\nu\bar{\nu})^{SM}} - 1;\ Br^{exp}/Br^{SM} + 1\sigma = 1.0060,\ Br^{exp}/Br^{SM} + 2\sigma = 1.0133$

  $\Rightarrow \boxed{|\lambda_{23k}| < \begin{smallmatrix} 0.04\,(1\sigma) \\ 0.07\,(2\sigma) \end{smallmatrix} \times (m(\tilde{e}^k_R)/100)}$

The obtained limits are the same as previously, but they are more robust since they do not vanish for $\lambda_{13k} \simeq \lambda_{23k}$.

$\underline{R_{\tau\mu}}$ $\quad R_{\tau\mu} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu}) = \dfrac{\tau_\mu Br(\tau \to \mu\nu\bar{\nu})}{\tau_\tau Br(\mu \to e\nu\bar{\nu})}$.

$R^{exp}_{\tau\mu}/R^{SM}_{\tau\mu} = \dfrac{|1 + r_{23k}|^2}{|1 + r_{12k}|^2}$.

Using relation (1): $R^{SM}_{\tau\mu} = 1309197$.

From $\tau_\mu = 2.19703 \times 10^{-6}$s [5], using $Br(\mu \to e\nu\bar{\nu}) = 100\%$, we derive $R^{exp}_{\tau\mu} = 1307486. \pm 9538.$ and therefore $R^{exp}_{\tau\mu}/R^{SM}_{\tau\mu} = 0.9987 \pm 0.0073$.

- $r_{23k} = \sqrt{R^{exp}_{\tau\mu}/R^{SM}_{\tau\mu}} - 1 = (-0.65 \pm 3.65) \times 10^{-3}$;

  $R^{exp}_{\tau\mu}/R^{SM}_{\tau\mu} + 1\sigma = 1.006,\ R^{exp}_{\tau\mu}/R^{SM}_{\tau\mu} + 2\sigma = 1.013$

  $\Rightarrow \boxed{|\lambda_{23k}| < \begin{smallmatrix} 0.05\,(1\sigma) \\ 0.07\,(2\sigma) \end{smallmatrix} \times (m(\tilde{e}^k_R)/100)}$

[1]Even looking at one single decay at a time, it is never possible to evade the effects of a non zero λ_{12k} which is the coupling affecting muon decay.

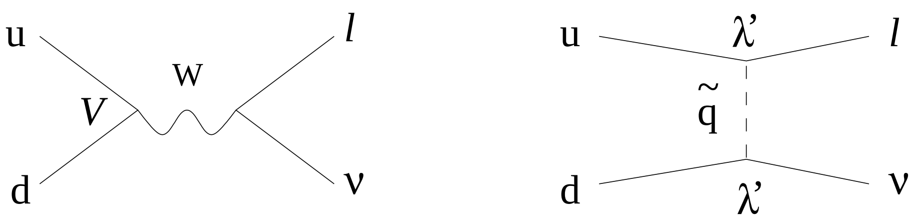

Figure 3: Pion decay and its R_p violating contribution.

- $r_{12k} = \sqrt{R^{SM}_{\tau\mu}/R^{exp}_{\tau\mu}} - 1 = (0.65 \pm 3.65) \times 10^{-3}$;
  $R^{SM}_{\tau\mu}/R^{exp}_{\tau\mu} + 1\sigma = 1.009$, $R^{SM}_{\tau\mu}/R^{exp}_{\tau\mu} + 2\sigma = 1.016$
  $\Rightarrow \boxed{|\lambda_{12k}| < \begin{smallmatrix} 0.05\,(1\sigma) \\ 0.07\,(2\sigma) \end{smallmatrix} \times (m(\tilde{e}^k_R)/100)}$

Again, $R_{\tau\mu}$'s sensitivity on λ is equivalent to R_τ's.

<u>R_π</u> $\quad R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$.
$R^{exp}_\pi/R^{SM}_\pi = \dfrac{|V^{SM}_{ud} + r'_{11k}|^2}{|V^{SM}_{ud} + r'_{21k}|^2}$ (see figure 3).
$R^{SM}_\pi = (1.2352 \pm 0.0005) \times 10^{-4}$[8]; from $R^{exp}_\pi = (1.230 \pm 0.004) \times 10^{-4}$ [5], we derive $R^{exp}_\pi/R^{SM}_\pi = 0.9958 \pm 0.0033$.

Taking $V^{SM}_{ud} = V^{exp}_{ud}$:

- $r'_{21k} = V^{SM}_{ud}(\sqrt{R^{exp}_\pi/R^{SM}_\pi} - 1) = (-2.1 \pm 1.6) \times 10^{-3}$;
  $R^{exp}_\pi/R^{SM}_\pi - 1\sigma = 0.9925$, $R^{exp}_\pi/R^{SM}_\pi - 2\sigma = 0.9892$
  $\Rightarrow \boxed{|\lambda'_{21k}| < \begin{smallmatrix} 0.05\,(1\sigma) \\ 0.06\,(2\sigma) \end{smallmatrix} \times (m(\tilde{d}^k_R)/100)}$
- $r'_{11k} = V^{SM}_{ud}(\sqrt{R^{SM}_\pi/R^{exp}_\pi} - 1) = (2.1 \pm 1.6) \times 10^{-3}$;
  $R^{SM}_\pi/R^{exp}_\pi - 1\sigma = 1.0009$: no limit, $R^{SM}_\pi/R^{exp}_\pi - 2\sigma = 0.9976$
  $\Rightarrow \boxed{|\lambda'_{11k}| < 0.03\,(2\sigma) \times (m(\tilde{d}^k_R)/100)}$

$\pi \to e\nu$ and $\pi \to \mu\nu$ decays are not measured separately, only their ratio R_π is measured, therefore it is not possible to derive separate limits on λ'_{11k} and λ'_{21k}.

1.1.3 $\tau \to \pi\nu_\tau$ decay

$\underline{\tau \to \pi\nu_\tau}$ This process was first considered by Bhattacharyya et al. [2].
$Br(\tau \to \pi\nu_\tau) = \Gamma(\tau \to \pi\nu_\tau)\tau_\tau/\hbar$,
$Br^{exp}(\tau \to \pi\nu_\tau) = Br^{SM}(\tau \to \pi\nu_\tau) \times |1 + r'_{31k}/V_{ud}|^2$.
$\Gamma(\tau \to \pi\nu_\tau) = |V_{ud}|^2 \times \dfrac{G_F^2 f_\pi^2 m_\tau^3}{16\pi} \times (1 - m_\pi^2/m_\tau^2)^2 \times (1+\text{radiative corrections})$
and $Br^{SM}(\tau \to \pi\nu_\tau) = (11.07 \pm 0.02)\% \times \dfrac{\tau_\tau}{295.10^{-15}}$ [9], using $f_\pi = 130.7 \pm 0.1 \pm 1.3$ MeV $\Rightarrow Br^{SM}(\tau \to \pi\nu_\tau) = (10.91 \pm 0.05)\%$, to be compared to $Br^{exp}(\tau \to \pi\nu_\tau) = (11.07 \pm 0.18)\%$ [5].
$Br^{exp}(\tau \to \pi\nu_\tau)/Br^{SM}(\tau \to \pi\nu_\tau) = 1.015 \pm 0.017$;
$r'_{31k} = |V_{ud}|(\sqrt{Br^{exp}/Br^{SM}} - 1) = (7.1 \pm 8.0) \times 10^{-3}$;
$Br^{exp}/Br^{SM} + 1\sigma = 1.032$, $Br^{exp}/Br^{SM} + 2\sigma = 1.049$,
$\Rightarrow \boxed{|\lambda'_{31k}| < {}^{0.10\,(1\sigma)}_{0.13\,(2\sigma)} \times (m(\tilde{d}_R^k)/100)}$

$\underline{R_{\tau\pi}}$ To get rid of the uncertainty on f_π, we define the following ratio:
$R_{\tau\pi} = \dfrac{\Gamma(\tau \to \pi\nu_\tau)}{\Gamma(\pi \to \mu\nu_\mu)} = \dfrac{\tau_\pi Br(\tau \to \pi\nu_\tau)}{\tau_\tau Br(\pi \to \mu\nu_\mu)}$.
$R_{\tau\pi}^{exp} = R_{\tau\pi}^{SM} \times \dfrac{|V_{ud} + r'_{31k}|^2}{|V_{ud} + r'_{21k}|^2}$.
$R_{\tau\pi}^{SM} = \dfrac{m_\tau^3}{2m_\pi m_\mu^2} \dfrac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} \times (1 + r)$, where r accounts for the radiative corrections.

From $r = 0.0016 \pm 0.0014$ [9], we derive $R_{\tau\pi}^{SM} = 9774.2 \pm 46.9$, and from $Br(\pi \to \mu\nu) = (99.9877 \pm 0.00004)\%$, $\tau_\pi = (2.6033 \pm 0.0005) \times 10^{-8}$s [5]:
$R_{\tau\pi}^{exp} = 9914.7 \pm 167.2 \Rightarrow R_{\tau\pi}^{exp}/R_{\tau\pi}^{SM} = 1.014 \pm 0.018$.

- $r'_{31k} = |V_{ud}| \times (\sqrt{R_{\tau\pi}^{exp}/R_{\tau\pi}^{SM}} - 1) = (7.0 \pm 8.3) \times 10^{-3}$;
  $R_{\tau\pi}^{exp}/R_{\tau\pi}^{SM} + 1\sigma = 1.032$, $R_{\tau\pi}^{exp}/R_{\tau\pi}^{SM} + 2\sigma = 1.050$,
  $\Rightarrow \boxed{|\lambda'_{31k}| < {}^{0.10\,(1\sigma)}_{0.12\,(2\sigma)} \times (m(\tilde{d}_R^k)/100)}$
- $r'_{21k} = |V_{ud}| \times (\sqrt{R_{\tau\pi}^{SM}/R_{\tau\pi}^{exp}} - 1) = (-6.9 \pm 8.3) \times 10^{-3}$;
  $R_{\tau\pi}^{SM}/R_{\tau\pi}^{exp} + 1\sigma = 1.003$, $R_{\tau\pi}^{SM}/R_{\tau\pi}^{exp} + 2\sigma = 1.020$,

$$\Rightarrow \boxed{|\lambda'_{21k}| < \begin{smallmatrix} 0.03\,(1\sigma) \\ 0.08\,(2\sigma) \end{smallmatrix} \times (m(\tilde{d}^k_R)/100)}$$

The result is slightly better than with $\tau \to \pi\nu$ only, partly by chance. $Br(\tau \to \pi\nu)$ is slightly above expectation, and $Br(\pi \to \mu\nu)$ as well (the expected value is 0.985 ± 0.02), therefore their ratio is closer to the SM value.

1.1.4 $D \to Kl\nu$ decays

These processes were first studied by Bhattacharyya et al. in [2]; again, they allow to test lepton universality in weak decays.

$$\left\{ \begin{array}{ll} R_{D^0} & = \Gamma(D^0 \to K^-\mu^+\nu_\mu)/\Gamma(D^0 \to K^-e^+\nu_e) \\ R^*_{D^+} & = \Gamma(D^+ \to \bar{K}^{*0}\mu^+\nu_\mu)/\Gamma(D^+ \to \bar{K}^{*0}e^+\nu_e), \\ R_{D^+} & = \Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)/\Gamma(D^+ \to \bar{K}^0e^+\nu_e) \\ & = Br(D^+ \to \bar{K}^0\mu^+\nu_\mu)/Br(D^+ \to \bar{K}^0e^+\nu_e). \end{array} \right.$$

The relevant Feynman diagrams are the same as in figure 1 with c replacing d, and s replacing u lines.

$$\frac{R^{exp}_{D^0}}{R^{SM}_{D^0}} = \frac{R^{*exp}_{D^+}}{R^{*SM}_{D^+}} = \frac{R^{exp}_{D^+}}{R^{SM}_{D^+}} = \frac{|1 + r'_{22k}|^2}{|1 + r'_{12k}|^2}.$$

$$\left\{ \begin{array}{l} \Gamma(D^0 \to K^-e^+\nu_e)/\Gamma(K^-\pi^+) = 0.90 \pm 0.07 \\ \Gamma(D^0 \to K^-\mu^+\nu_\mu)/\Gamma(K^-\pi^+) = 0.84 \pm 0.04 \end{array} \right. ,$$
$$\left\{ \begin{array}{l} \Gamma(D^+ \to \bar{K}^{*0}e^+\nu_e)/\Gamma(K^-\pi^+\pi^+) = 0.515 \pm 0.055 \\ \Gamma(D^+ \to \bar{K}^{*0}\mu^+\nu_\mu)/\Gamma(K^-\pi^+\pi^+) = 0.56 \pm 0.07 \end{array} \right. ,$$
$$\left\{ \begin{array}{l} Br(D^+ \to \bar{K}^0e^+\nu_e) = (6^{+2.2}_{-1.3} \pm 0.7)\% \\ Br(D^+ \to \bar{K}^0\mu^+\nu_\mu) = (7^{+2.8}_{-1.6} \pm 1.2)\% \end{array} \right. \quad [5].$$

In averaging the branching ratio measurements of each leptonic channel, we do not want to take into account those obtained using both e and μ with a small phase space correction, therefore we do not use the PDG's average and recompute our own average of $D^+ \to \bar{K}^{*0}e^+\nu_e$ and $D^0 \to \bar{K}^0e^+\nu_e$.

$$\text{We get} \left\{ \begin{array}{l} R^{exp}_{D^0} = 0.933 \pm 0.085 \\ R^{*exp}_{D^+} = 1.09 \pm 0.17 \\ R^{exp}_{D^+} \simeq 1.2 \pm 0.6 \end{array} \right.$$

Following Altarelli et al. [10], we take $R^{SM}_{D^+} = R^{*SM}_{D^+} = R^{SM}_{D^0} = (1.03)^{-1}$.

$\underline{R_{D^0}}$

- $r'_{22k} = \sqrt{R^{exp}_{D^0}/R^{SM}_{D^0}} - 1 = (-2.0 \pm 4.5) \times 10^{-2}$;
  $R^{exp}_{D^0}/R^{SM}_{D^0} + 1\sigma = 1.05$, $R^{exp}_{D^0}/R^{SM}_{D^0} + 2\sigma = 1.14$,
  $\Rightarrow \boxed{|\lambda'_{22k}| < {}^{0.13\,(1\sigma)}_{0.21\,(2\sigma)} \times (m(\tilde{d}^k_R)/100)}$
- $r'_{12k} = \sqrt{R^{SM}_{D^0}/R^{exp}_{D^0}} - 1 = (2.0 \pm 4.6) \times 10^{-2}$;
  $R^{SM}_{D^0}/R^{exp}_{D^0} + 1\sigma = 1.14$, $R^{SM}_{D^0}/R^{exp}_{D^0} + 2\sigma = 1.23$,
  $\Rightarrow \boxed{|\lambda'_{12k}| < {}^{0.21\,(1\sigma)}_{0.27\,(2\sigma)} \times (m(\tilde{d}^k_R)/100)}$

$\underline{R^*_{D^+}}$

- $r'_{22k} = \sqrt{R^{*exp}_{D^+}/R^{*SM}_{D^+}} - 1 = (5.9 \pm 8.3) \times 10^{-2}$;
  $R^{*exp}_{D^+}/R^{*SM}_{D^+} + 1\sigma = 1.30$, $R^{*exp}_{D^+}/R^{*SM}_{D^+} + 2\sigma = 1.47$,
  $\Rightarrow \boxed{|\lambda'_{22k}| < {}^{0.30\,(1\sigma)}_{0.38\,(2\sigma)} \times (m(\tilde{d}^k_R)/100)}$
- $r'_{12k} = \sqrt{R^{*SM}_{D^+}/R^{*exp}_{D^+}} - 1 = (-5.6 \pm 7.4) \times 10^{-2}$;
  $R^{*SM}_{D^+}/R^{*exp}_{D^+} + 1\sigma = 1.03$, $R^{*SM}_{D^+}/R^{*exp}_{D^+} + 2\sigma = 1.17$,
  $\Rightarrow \boxed{|\lambda'_{12k}| < {}^{0.10\,(1\sigma)}_{0.23\,(2\sigma)} \times (m(\tilde{d}^k_R)/100)}$

$\underline{R_{D^+}}$

- $r'_{22k} = \sqrt{R^{exp}_{D^+}/R^{SM}_{D^+}} - 1 = 0.11 \pm 0.28$;
  $R^{exp}_{D^+}/R^{SM}_{D^+} + 1\sigma = 1.81$, $R^{exp}_{D^+}/R^{SM}_{D^+} + 2\sigma = 2.42$,
  $\Rightarrow \boxed{|\lambda'_{22k}| < {}^{0.49\,(1\sigma)}_{0.61\,(2\sigma)} \times (m(\tilde{d}^k_R)/100)}$
- $r'_{12k} = \sqrt{R^{SM}_{D^+}/R^{exp}_{D^+}} - 1 = -0.09 \pm 0.23$;
  $R^{SM}_{D^+}/R^{exp}_{D^+} + 1\sigma = 1.25$, $R^{SM}_{D^+}/R^{exp}_{D^+} + 2\sigma = 1.67$,
  $\Rightarrow \boxed{|\lambda'_{12k}| < {}^{0.28\,(1\sigma)}_{0.44\,(2\sigma)} \times (m(\tilde{d}^k_R)/100)}$

The most stringent limits are obtained from $D^0 \to K^- l\nu$ and $D^+ \to \bar{K}^{*0} l\nu$ which are better measured than $D^+ \to \bar{K}^0 l\nu$. Nevertheless, we can combine the three of them to obtain a slightly improved limit later when combining all limits on λ'_{22k} and λ'_{12k} :

$$\begin{cases} r'^{\,comb}_{22k} = (-0.005 \pm 3.9) \times 10^{-2} \\ r'^{\,comb}_{12k} = (-0.3 \pm 3.9) \times 10^{-2} \end{cases}$$

1.2 $D_s \to l\nu_l$ decays

The relevant Feynman diagrams are those of figure 3 replacing $(u,\, d)$ by $(c,\, s)$.

$$R_{D_s} = \frac{\Gamma(D_s \to \tau\nu_\tau)}{\Gamma(D_s \to \mu\nu_\mu)} = \frac{Br(D_s \to \tau\nu_\tau)}{Br(D_s \to \mu\nu_\mu)}$$

$$R^{exp}_{D_s} = R^{SM}_{D_s} \times \frac{|V_{cs} + r'_{32k}|^2}{|V_{cs} + r'_{22k}|^2}$$

$$R^{SM}_{D_s} \simeq \frac{m^2_\tau}{m^2_\mu} \frac{(1 - m^2_\tau/m^2_{D_s})^2}{(1 - m^2_\mu/m^2_{D_s})^2},\ m_{D_s} = 1969.0 \pm 1.4 \text{ MeV} \Rightarrow R^{SM}_{D_s} \simeq 9.79.$$

Now, $Br(D_s \to \tau\nu_\tau) = (7.4 \pm 3.7)\%$, $\Gamma(D_s \to \mu\nu_\mu)/\Gamma(D_s \to \phi\pi) = 0.245 \pm 0.090$, $Br(D_s \to \phi\pi) = (3.6 \pm 0.9)\%$ [5] $\Rightarrow Br(D_s \to \mu\nu_\mu) = (8.8 \pm 3.9)10^{-3}$ and $R^{exp}_{D_S} = 8.4 \pm 5.6$.

Taking $V_{cs} = 0.974$ [5]:

- $r'_{32k} = V_{cs}(\sqrt{R^{exp}_{D_s}/R^{SM}_{D_s}} - 1) = -0.07 \pm 0.30$;
  $R^{exp}_{D_s}/R^{SM}_{D_s} + 1\sigma = 1.43$, $R^{exp}_{D_s}/R^{SM}_{D_s} + 2\sigma = 2.00$,
  $\Rightarrow \boxed{|\lambda'_{32k}| < \begin{smallmatrix} 0.36\,(1\sigma) \\ 0.52\,(2\sigma) \end{smallmatrix} \times (m(\tilde{d}^k_R)/100)}$
- $r'_{22k} = V_{cs}(\sqrt{R^{SM}_{D_s}/R^{exp}_{D_s}} - 1) = 0.08 \pm 0.35$;
  $R^{SM}_{D_s}/R^{exp}_{D_s} + 1\sigma = 1.94$, $R^{SM}_{D_s}/R^{exp}_{D_s} + 2\sigma = 2.71$,
  $\Rightarrow \boxed{|\lambda'_{22k}| < \begin{smallmatrix} 0.51\,(1\sigma) \\ 0.65\,(2\sigma) \end{smallmatrix} \times (m(\tilde{d}^k_R)/100)}$

Even if these decays are not yet well measured, they are the only constraint on λ'_{32k}.

On the other hand, because f_{D_s} is measured only very roughly ($f_{D_s} = (4.3^{+1.5+0.4}_{-1.3-0.4})10^2$ MeV [11]) it is not possible to derive separate limits from each leptonic channel.

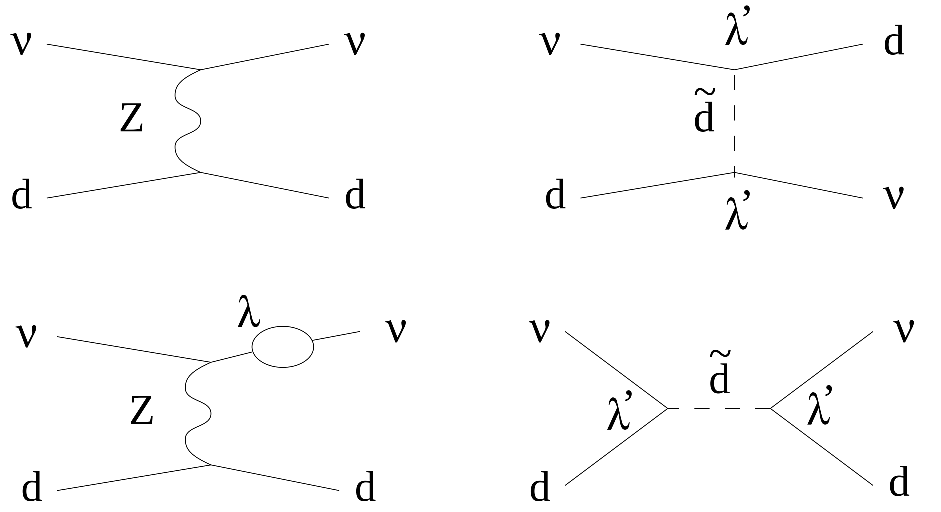

Figure 4: ν-hadron scattering and the R_p violating contributions to the measured coupling.

1.3 Neutral current processes

Now, we test a different type of diagrams: ν-hadron, νe and e-hadron scattering, see for instance figure 4 for neutrino DIS.
In the SM of electroweak interactions, the vector and axial-vector couplings of the Z to leptons are $\begin{cases} g_V^f = T_3^f - 2q_f \sin^2\theta_W \\ g_A^f = T_3^f \end{cases}$
with $T_3^u = 1/2$, $T_3^d = -1/2$, $T_3^\nu = 1/2$, $T_3^e = -1/2$.

We use the SM expectations quoted in reference [5] which assume $M_Z = 91.1867 \pm 0.0020$ GeV, $M_H = M_Z$, $m_t = 173 \pm 4$ GeV, $\alpha_s = 0.1214 \pm 0.0031$ and $1/\hat{\alpha}(M_Z) = 127.90 \pm 0.07$.

1.3.1 ν_μ deep inelastic scattering

$$\begin{cases} \epsilon_L(f) = (g_V^f + g_A^f)/2 = T_3^f - q_f \sin^2\theta_W \\ \epsilon_R(f) = (g_V^f - g_A^f)/2 = -q_f \sin^2\theta_W \end{cases}$$
$$\Rightarrow \begin{cases} \epsilon_L(d) = -1/2 + 1/3 \sin^2\theta_W \\ \epsilon_R(d) = 1/3 \sin^2\theta_W \end{cases} \quad \text{(with no radiative correction).}$$
Here, not only one, but several R_p violating diagrams can contribute to

process $\nu d \to \nu d$ (including loop corrections as well). On the other hand, we cannot use $\epsilon_L(u)$, $\epsilon_L(u)$ because there is no R_p violating contribution to $\nu u \to \nu u$ scatterings.

$$\begin{cases} \epsilon_L^{exp}(d) = \epsilon_L^{SM}(d) - r'_{21k} - \epsilon_L^{SM}(d) r_{12k} \\ \epsilon_R^{exp}(d) = \epsilon_R^{SM}(d) + r'_{2j1} - \epsilon_R^{SM}(d) r_{12k} \end{cases}$$

We find in [5], including the radiative corrections:

$$\begin{cases} \epsilon_L^{SM}(d) = -0.4292 \pm 0.0002 \\ \epsilon_R^{SM}(d) = 0.0775 \pm 0.0001 \end{cases} \text{ and } \begin{cases} \epsilon_L^{exp}(d) = -0.440 \pm 0.011 \\ \epsilon_R^{exp}(d) = -0.027^{+0.077}_{-0.048} \end{cases}$$

The most recent experimental input comes from CCFR in 1997 [12].

- $r_{12k} = \dfrac{\epsilon_L^{SM}(d) - \epsilon_L^{exp}(d)}{\epsilon_L^{SM}(d)} = (-2.5 \pm 2.6) \times 10^{-2}$;
  $\epsilon_L^{exp}(d) + 1\sigma = -0.429$, $\epsilon_L^{exp}(d) + 2\sigma = -0.418$
  $\Rightarrow \boxed{|\lambda_{12k}| < {}^{0.02\,(1\sigma)}_{0.13\,(2\sigma)} \times (m(\tilde{e}_R^k)/100)}$
- $r'_{21k} = \epsilon_L^{SM}(d) - \epsilon_L^{exp}(d) = (1.1 \pm 1.1) \times 10^{-2}$;
  $\epsilon_L^{exp}(d) - 1\sigma = -0.451$, $\epsilon_L^{exp}(d) - 2\sigma = -0.462$
  $\Rightarrow \boxed{|\lambda'_{21k}| < {}^{0.12\,(1\sigma)}_{0.15\,(2\sigma)} \times (m(\tilde{d}_R^k)/100)}$
- $r_{12k} = \dfrac{\epsilon_R^{SM}(d) - \epsilon_R^{exp}(d)}{\epsilon_R^{SM}(d)}$; $\epsilon_R^{exp}(d) - 1\sigma = -0.075$, $\epsilon_R^{exp}(d) - 2\sigma = -0.123$
  $\Rightarrow \boxed{|\lambda_{12k}| < {}^{1.1\,(1\sigma)}_{1.3\,(2\sigma)} \times (m(\tilde{e}_R^k)/100)}$
- $r'_{2j1} = \epsilon_R^{exp}(d) - \epsilon_R^{SM}(d) = -0.10 \pm 0.08$;
  $\epsilon_R^{exp}(d) + 1\sigma = 0.050$: no limit, $\epsilon_R^{exp}(d) + 2\sigma = 0.127$
  $\Rightarrow \boxed{|\lambda'_{2j1}| < 0.18\,(2\sigma) \times (m(\tilde{d}_L^j)/100)}$

$\epsilon_R(d)$ is much less precisely measured than $\epsilon_L(d)$ so it is useless in constraining λ_{12k}; however for $j = 3$, it gives the strictest limit on λ'_{2j1}.
The limit on λ'_{21k} is slightly worse than it was in 1989 [1] (0.11 at 1σ level) although the experimental result improved (it was $\epsilon_L(d)^{exp} = -0.429 \pm 0.014$). This is probably because the old central value was closer to the expected value, although the radiative correction might have been less precisely calculated at the time.

1.3.2 $\nu_\mu e$ scattering

The processes are those shown in figure 4 replacing $(\lambda', d, \tilde{q})$ by $(\lambda, e, \tilde{l})$.

$$\left\{ \begin{array}{l} g_V^{\nu e} = 2 g_V^{\nu_\mu} g_V^e \\ g_A^{\nu e} = 2 g_A^{\nu_\mu} g_A^e \end{array} \right. ,$$

$$\left\{ \begin{array}{l} g_L = (g_V^{\nu e} + g_A^{\nu e})/2 = -1/2 + \sin^2\theta_W \\ g_R = (g_V^{\nu e} - g_A^{\nu e})/2 = \sin^2\theta_W \end{array} \right. \quad \text{(with no radiative correction).}$$

$$\left\{ \begin{array}{l} g_L^{exp} = g_L^{SM} - (1 + g_L^{SM}) r_{12k} \\ g_R^{exp} = g_R^{SM} + r_{121} + r_{231} - g_R^{SM} r_{12k} \end{array} \right.$$

In [5] we find, including the radiative corrections:

$$\left\{ \begin{array}{l} (g_V^{\nu e})^{SM} = -0.0395 \pm 0.0005 \\ (g_A^{\nu e})^{SM} = -0.5064 \pm 0.0002 \end{array} \right. \Rightarrow \left\{ \begin{array}{l} g_L^{SM} = -0.2729 \pm 0.0003 \\ g_R^{SM} = 0.2334 \pm 0.0003 \end{array} \right.$$

$$\text{and} \left\{ \begin{array}{l} (g_V^{\nu e})^{exp} = -0.041 \pm 0.015 \\ (g_A^{\nu e})^{exp} = -0.507 \pm 0.014 \end{array} \right. \Rightarrow \left\{ \begin{array}{l} g_L^{exp} = -0.274 \pm 0.010 \\ g_R^{exp} = 0.233 \pm 0.010 \end{array} \right.$$

- $r_{12k} = \dfrac{g_L^{SM} - g_L^{exp}}{1 + g_L^{SM}} = (1.5 \pm 13.8) \times 10^{-3}$;
  $g_L^{exp} - 1\sigma = -0.284$, $g_L^{exp} - 2\sigma = -0.294$
  $\Rightarrow \boxed{|\lambda_{12k}| < {}^{0.10\,(1\sigma)}_{0.14\,(2\sigma)} \times (m(\tilde{e}_R^k)/100)}$

- $k \neq 1$: $r_{12k} = \dfrac{g_R^{SM} - g_R^{exp}}{g_R^{SM}}$; $g_R^{exp} - 1\sigma = 0.223$, $g_R^{exp} - 2\sigma = 0.213$
  $\Rightarrow \boxed{|\lambda_{12k}| < {}^{0.17\,(1\sigma)}_{0.24\,(2\sigma)} \times (m(\tilde{e}_R^k)/100) \quad (k \neq 1)}$

- $r_{231} = -g_R^{SM} + g_R^{exp} = (-0.4 \pm 10.) \times 10^{-3}$, $r_{121} = \dfrac{g_R^{exp} - g_R^{SM}}{1 - g_R^{SM}} = (-0.5 \pm 13.1) \times 10^{-3}$; $g_R^{exp} + 1\sigma = 0.243$, $g_R^{exp} + 2\sigma = 0.253$
  $\Rightarrow \boxed{|\lambda_{231}| < {}^{0.08\,(1\sigma)}_{0.11\,(2\sigma)} \times (m(\tilde{\tau}_L)/100)}$
  $\boxed{|\lambda_{121}| < {}^{0.09\,(1\sigma)}_{0.13\,(2\sigma)} \times (m(\tilde{e}_L)/100)}$
  λ_{121} is better constrained by charged current universality and several other processes.

It is to be noted that the most recent experimental result included in the PDG compilation comes from Charm II in 1994 [13].

1.3.3 Atomic parity violation (APV)

The processes involved are again those shown in figure 4 replacing ν by e and doubling the number of possibilities with u instead of d.

$$\left\{\begin{array}{l} C_{1u} = 2g_A^e g_V^u = -1/2 + 4/3\sin^2\theta_W \\ C_{1d} = 2g_A^e g_V^d = \ \ 1/2 - 2/3\sin^2\theta_W \\ C_{2u} = 2g_V^e g_A^u = -1/2 + 2\sin^2\theta_W \\ C_{2d} = 2g_V^e g_A^d = \ \ 1/2 - 2\sin^2\theta_W \end{array}\right. , Q_W = -2((Z+A)C_{1u} + (2A-Z)C_{1d})$$

$$\left\{\begin{array}{l} C_{iu}^{exp} = C_{iu}^{SM} - r'_{11k} - C_{iu}^{SM} r_{12k}, \quad i = 1,2 \\ C_{1d}^{exp} = C_{1d}^{SM} + r'_{1j1} - C_{1d}^{SM} r_{12k} \\ C_{2d}^{exp} = C_{2d}^{SM} - r'_{1j1} - C_{2d}^{SM} r_{12k} \end{array}\right.$$

$$Q_W^{exp} = Q_W^{SM}(1 - r_{12k}) + 2((Z+A)r'_{11k} - (2A-Z)r'_{1j1})$$

One can use either the C coefficients, or the weak charge Q_W; the best results are obtained with Cesium ($Z = 55$, $A = 133$) [5]:

$$\left\{\begin{array}{l} C_{1u}^{SM} = -0.1885 \pm 0.0003 \\ C_{1d}^{SM} = 0.3412 \pm 0.0002 \\ (C_{2u} - C_{2d}/2)^{SM} = -0.0488 \pm 0.0008 \end{array}\right. , Q_W^{SM} = -73.12 \pm 0.06$$

$$\left\{\begin{array}{l} C_{1u}^{exp} = -0.216 \pm 0.046 \\ C_{1d}^{exp} = 0.361 \pm 0.041 \\ (C_{2u} - C_{2d}/2)^{exp} = -0.03 \pm 0.12 \end{array}\right. , Q_W^{exp} = -72.41 \pm 0.25 \pm 0.80$$

<u>Using the C coefficients:</u>

- $r_{12k} = \dfrac{C_{1u}^{SM} - C_{1u}^{exp}}{C_{1u}^{SM}}$; $C_{1u}^{exp} + 1\sigma = -0.170$, $C_{1u}^{exp} + 2\sigma = -0.124$.

  $\Rightarrow \boxed{|\lambda_{12k}| < \begin{smallmatrix} 0.25\,(1\sigma) \\ 0.48\,(2\sigma) \end{smallmatrix} \times (m(\tilde{e}_R^k)/100)}$

- $r'_{11k} = C_{1u}^{SM} - C_{1u}^{exp}$; $C_{1u}^{exp} - 1\sigma = -0.262$, $C_{1u}^{exp} - 2\sigma = -0.308$.

  $\Rightarrow \boxed{|\lambda'_{11k}| < \begin{smallmatrix} 0.22\,(1\sigma) \\ 0.28\,(2\sigma) \end{smallmatrix} \times (m(\tilde{d}_R^k)/100)}$

- $r_{12k} = \dfrac{C_{1d}^{SM} - C_{1d}^{exp}}{C_{1d}^{SM}}$; $C_{1d}^{exp} - 1\sigma = 0.320$, $C_{1d}^{exp} - 2\sigma = 0.279$.

  $\Rightarrow \boxed{|\lambda_{12k}| < \begin{smallmatrix} 0.20\,(1\sigma) \\ 0.35\,(2\sigma) \end{smallmatrix} \times (m(\tilde{e}_R^k)/100)}$

- $r'_{1j1} = -C_{1d}^{SM} + C_{1d}^{exp}$; $C_{1d}^{exp} + 1\sigma = 0.402$, $C_{1d}^{exp} + 2\sigma = 0.443$.

  $\Rightarrow \boxed{|\lambda'_{1j1}| < \begin{smallmatrix} 0.20\,(1\sigma) \\ 0.26\,(2\sigma) \end{smallmatrix} \times (m(\tilde{q}_L^j)/100)}$

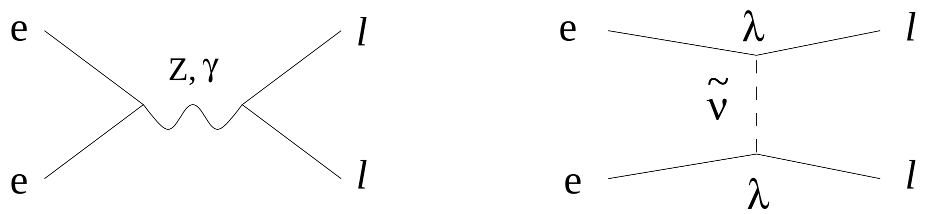

Figure 5: e^+e^- annihilation to l^+l^- and the R_p violating contribution to the same final state.

$C_{2u} - C_{2d}/2$ is obviously less precisely determined, therefore we do not show the much weaker limits coming from this quantity.

Using Q_W:

- $r_{12k} = \dfrac{Q_W^{SM} - Q_W^{exp}}{Q_W^{SM}} = (9.7 \pm 11.4) \times 10^{-3}$, $r'_{11k} = \dfrac{Q_W^{exp} - Q_W^{SM}}{2(Z+A)} = (1.9 \pm 2.2) \times 10^{-3}$; $Q_W^{exp} + 1\sigma = -71.57$, $Q_W^{exp} + 2\sigma = -70.73$

  $\Rightarrow \boxed{|\lambda_{12k}| < {}^{0.12\,(1\sigma)}_{0.15\,(2\sigma)} \times (m(\tilde{e}_R^k)/100)}$

  $\boxed{|\lambda'_{11k}| < {}^{0.05\,(1\sigma)}_{0.06\,(2\sigma)} \times (m(\tilde{d}_R^k)/100)}$

- $r'_{1j1} = \dfrac{Q_W^{SM} - Q_W^{exp}}{2A - Z} = (-3.4 \pm 4.0) \times 10^{-3}$;
  $Q_W^{exp} - 1\sigma = -73.25$, $Q_W^{exp} - 2\sigma = -74.09$

  $\Rightarrow \boxed{|\lambda'_{1j1}| < {}^{0.02\,(1\sigma)}_{0.04\,(2\sigma)} \times (m(\tilde{q}_L^j)/100)}$

The weak charge Q_W does a much better job than the C coefficients. Concerning the assumption of no other non standard contribution to APV, the impact of a possible second Z boson is discussed in reference [14] in which it is shown that Z_2 effects could exactly compensate those of a non zero λ'_{11k} or λ'_{1j1}.

1.3.4 A_{FB} asymmetries in e^+e^- collisions at the Z peak.

At the Z peak: $A_{FB}^{0,f} = \frac{3}{4}A_e A_f$; $A_f = \dfrac{2g_V^f g_A^f}{g_V^{f2} + g_A^{f2}}$.

$(A_{FB}^{0,l})^{exp} = \dfrac{(A_{FB}^{0,l})^{SM}}{|1+r|^2}$ (see diagrams figure 5), $(A_{FB}^{0,q})^{exp} = \dfrac{(A_{FB}^{0,q})^{SM}}{|1+r'|^2}$.

$$\begin{cases} (A_{FB}^{0,e})^{exp} = (A_{FB}^{0,e})^{SM}/|1+r_{ijk}|^2, & ijk = 121, 131 \\ (A_{FB}^{0,\mu})^{exp} = (A_{FB}^{0,\mu})^{SM}/|1+r_{ijk}|^2, & ijk = 121, 122, 132, 231 \\ (A_{FB}^{0,\tau})^{exp} = (A_{FB}^{0,\tau})^{SM}/|1+r_{ijk}|^2, & ijk = 123, 133, 131, 231 \\ (A_{FB}^{0,s})^{exp} = (A_{FB}^{0,s})^{SM}/|1+r'_{1j2}|^2 & \\ (A_{FB}^{0,c})^{exp} = (A_{FB}^{0,c})^{SM}/|1+r'_{12k}|^2 & \\ (A_{FB}^{0,b})^{exp} = (A_{FB}^{0,b})^{SM}/|1+r'_{1j3}|^2. & \end{cases}$$

From [5], including the radiative corrections: $\begin{cases} (A_{FB}^{0,l})^{SM} = 0.0162 \pm 0.0003 \\ (A_{FB}^{0,s})^{SM} = 0.1031 \pm 0.0009 \\ (A_{FB}^{0,c})^{SM} = 0.0736 \pm 0.0007 \\ (A_{FB}^{0,b})^{SM} = 0.1030 \pm 0.0009 \end{cases}$

and $\begin{cases} (A_{FB}^{0,e})^{exp} = 0.0160 \pm 0.0024 & (A_{FB}^{0,s})^{exp} = 0.118 \pm 0.018 \\ (A_{FB}^{0,\mu})^{exp} = 0.0163 \pm 0.0014 & (A_{FB}^{0,c})^{exp} = 0.0741 \pm 0.0048 \\ (A_{FB}^{0,\tau})^{exp} = 0.0192 \pm 0.0018 & (A_{FB}^{0,b})^{exp} = 0.0984 \pm 0.0024. \end{cases}$

- $r_{ijk} = \sqrt{\frac{(A_{FB}^{0,e})^{SM}}{(A_{FB}^{0,e})^{exp}}} - 1 = (0.6 \pm 7.6) \times 10^{-2}$;
  $(A_{FB}^{0,e})^{exp} - 1\sigma = 0.0136$, $(A_{FB}^{0,e})^{exp} - 2\sigma = 0.0112$
  $\Rightarrow \boxed{|\lambda_{ijk}| < {}^{0.25\,(1\sigma)}_{0.37\,(2\sigma)} \times (m(\tilde{\nu})/100), \quad ijk = 121, 131}$
- $r_{ijk} = \sqrt{\frac{(A_{FB}^{0,\mu})^{SM}}{(A_{FB}^{0,\mu})^{exp}}} - 1 = (-0.3 \pm 4.3) \times 10^{-2}$;
  $(A_{FB}^{0,\mu})^{exp} - 1\sigma = 0.0149$, $(A_{FB}^{0,\mu})^{exp} - 2\sigma = 0.0135$
  $\Rightarrow \boxed{|\lambda_{ijk}| < {}^{0.17\,(1\sigma)}_{0.25\,(2\sigma)} \times (m(\tilde{\nu})/100), \quad ijk = 121, 122, 132, 231}$
- $r_{ijk} = \sqrt{\frac{(A_{FB}^{0,\tau})^{SM}}{(A_{FB}^{0,\tau})^{exp}}} - 1 = (-8.1 \pm 4.3) \times 10^{-2}$;
  $(A_{FB}^{0,\tau})^{exp} - 1\sigma = 0.0174$: no limit, $(A_{FB}^{0,\tau})^{exp} - 2\sigma = 0.0156$
  $\Rightarrow \boxed{|\lambda_{ijk}| < 0.11\,(2\sigma) \times (m(\tilde{\nu})/100), \quad ijk = 123, 133, 131, 231}$
- $r'_{1j2} = \sqrt{\frac{(A_{FB}^{0,s})^{SM}}{(A_{FB}^{0,s})^{exp}}} - 1 = (-6.5 \pm 7.1) \times 10^{-2}$;

$(A_{FB}^{0,s})^{exp} - 1\sigma = 0.100$, $(A_{FB}^{0,s})^{exp} - 2\sigma = 0.082$

$$\Rightarrow \boxed{|\lambda'_{1j2}| < {}^{0.10\,(1\sigma)}_{0.28\,(2\sigma)} \times (m(\tilde{q}_L^j)/100)}$$

- $r'_{12k} = \sqrt{\frac{(A_{FB}^{0,c})^{SM}}{(A_{FB}^{0,c})^{exp}}} - 1 = (-0.3 \pm 3.2) \times 10^{-2}$;

  $(A_{FB}^{0,c})^{exp} - 1\sigma = 0.0693$, $(A_{FB}^{0,c})^{exp} - 2\sigma = 0.0645$

  $$\Rightarrow \boxed{|\lambda'_{12k}| < {}^{0.14\,(1\sigma)}_{0.21\,(2\sigma)} \times (m(\tilde{d}_R^k)/100)}$$

- $r'_{1j3} = \sqrt{\frac{(A_{FB}^{0,b})^{SM}}{(A_{FB}^{0,b})^{exp}}} - 1 = (2.3 \pm 1.3) \times 10^{-2}$;

  $(A_{FB}^{0,b})^{exp} - 1\sigma = 0.0960$, $(A_{FB}^{0,b})^{exp} - 2\sigma = 0.0936$

  $$\Rightarrow \boxed{|\lambda'_{1j3}| < {}^{0.15\,(1\sigma)}_{0.18\,(2\sigma)} \times (m(\tilde{q}_L^j)/100)}$$

Originally, Barger et al. [1] used Forward-Backward asymmetries at lower energies (35-40 GeV). Now, we take advantage of the very precise measurements done at LEP and SLC (the measurement of $e^+e^- \to s\bar{s}$ is even entirely new). Only the measurement of $\mu^+\mu^-$ gets worse at LEP/SLC energies with 8.6% relative precision when it was 5.5% ($T_3^e T_3^\mu = 0.272 \pm 0.015$ [1]).

1.4 Summary

For each process and each λ or λ', four numbers are given in table 1 (λ) or 2 (λ'): (1) the limit derived by initial authors at 1σ level, (2) the limit given in the most recent published review (Bhattacharyya [15]) at 1σ level, (3) the present update at 1σ level, and (4) same as (3) at 2σ level.

With latest experimental results, most of the limits become more stringent, with a few exceptions: λ_{121}, λ_{122}, λ_{132}, λ_{231} from $A_{FB}^{\mu^+\mu^-}$, λ'_{21k} from ν_μ DIS and λ'_{31k} from $\tau \to \pi\nu_\tau$. The best limits on λ are obtained with charged current universality, R_τ and $R_{\tau\mu}$.

The limits coming from neutrinoless double β decay will be discussed in next section together with other SM forbidden processes; top decays as well, as they are still hardly measured.

Now, we are aware of the fact that the method used so far to extract limits gives 'optimistic' results, in the sense that the couplings appear more constrained than they should. Therefore, we also display the results in terms

	(a) CC univ.	(b) R_τ	(c) $R_{\tau\mu}$	(d) $\nu_\mu e$ scatt.	(e) $A_{FB}^{e^+e^-}$	$A_{FB}^{\mu^+\mu^-}$	$A_{FB}^{\tau^+\tau^-}$
					$k=1$	$k\neq 3$	$k=3$
λ_{12k}	0.04		–	0.34	–	0.10 (2σ)	0.24
	0.05		–	0.34	–	–	–
	0.04		0.05	0.10	0.25	0.17	–
	0.05		0.07	0.14	0.37	0.25	0.11
					$k=1$	$k=2$	$k\neq 2$
λ_{13k}		0.10			–	0.10 (2σ)	0.24
		0.06			–	–	–
		0.05			0.25	0.17	–
		0.07			0.37	0.25	0.11
				$k=1$		$k=1$	$k=1$
λ_{23k}		0.12	0.09	0.26		0.10 (2σ)	0.24
		0.06	–	0.26		–	–
		0.05	0.05	0.08		0.17	–
		0.07	0.07	0.11		0.25	0.11

Table 1: Limits on λ from tree level processes; a factor of $\tilde{m}/100$ is implicit everywhere; see section 1.3 for the meaning of each line in a box.

of λ^2 or λ'^2 (which by the way are often negative) and let the reader extract a limit using his preferred method in these regions which are close to unphysical results. A summary of λ^2 (λ'^2) estimations is given in table 3, together with their combination inside each set of indices, assuming independent measurements.

All of the λ^2 and λ'^2 are compatible with zero at the 1 σ level, except 3 negative (${\lambda'}^2_{12k}$, ${\lambda'}^2_{13k}$ and ${\lambda'}^2_{2j1}$) and 2 positive (λ^2_{12k} and ${\lambda'}^2_{1j3}$) deviations at the 2 σ level.

2 Loop, box, FCNC processes and top decays

They were generally studied more recently than the previous processes, therefore the corresponding published limits are more up to date. These limits are less easy to calculate; besides, the dependence of the result in $\tilde{m}$ can be more complicated than just a factor of $\tilde{m}/100$.

	(a) CC univ.	(f) R_π	(g) ν_μ DIS	(h) APV	(i) $A_{FB}^{q\bar{q}}$	(j) $D \to Kl\nu$	(k) $\tau \to \pi\nu_\tau$	(l) $R_{\tau\pi}$	(m) R_{D_s}
λ'_{11k}	0.03 0.02 – 0.02	0.05 0.05 – 0.03		– – 0.05 0.06					
λ'_{12k}	– – – 0.04				0.45 – 0.14 0.21	– 0.36 0.10 0.23			
λ'_{13k}	– – – 0.37								
λ'_{1j1}				– 0.035 0.02 0.04					
λ'_{1j2}					– – 0.10 0.28				
λ'_{1j3}					0.26 – 0.15 0.18				
λ'_{21k}		0.09 0.09 0.05 0.06	0.11 0.11 0.12 0.15					– – 0.03 0.08	
λ'_{22k}						– 0.17 0.13 0.21			– – 0.51 0.65
λ'_{2j1}			0.22 (2σ) 0.22 (2σ) – 0.18						
λ'_{31k}							– 0.14 0.10 0.13	– – 0.10 0.12	
λ'_{32k}									– – 0.36 0.52

Table 2: Limits on λ' from tree level processes; a factor of $\tilde{m}/100$ is implicit everywhere; see section 1.3 for the meaning of each line in a box.

	(a) CC univ.	(b) R_τ	(c) $R_{\tau\mu}$	(d) $\nu_\mu e$ scatt.	(e) $A_{FB}^{l^+l^-}$	(g) ν_μ DIS	(h) APV	combination
λ^2_{12k}	0.10 ± 0.07		0.04 ± 0.24	0.10 ± 0.91		-1.6 ± 1.7	0.64 ± 0.76	0.10 ± 0.07
$k \neq 3$					-0.2 ± 2.8			not
λ^2_{121}				-0.04 ± 0.86	0.4 ± 5.0			contri-
λ^2_{123}					-5.3 ± 2.8			buting
λ^2_{13k}		0.02 ± 0.24						0.02 ± 0.24
$k \neq 2$					-5.3 ± 2.8			not
λ^2_{131}					0.4 ± 5.0			contri-
λ^2_{132}					-0.2 ± 2.8			buting
λ^2_{23k}		-0.02 ± 0.24	$-0.04 \pm 0.24^\dagger$					-0.02 ± 0.24
λ^2_{231}				-0.03 ± 0.66	-0.2 ± 2.8			not con-
					-5.3 ± 2.8			tributing

	(a) CC univ.	(f) R_π	(g) ν_μ DIS	(h) APV	(i) $A_{FB}^{q\bar{q}}$	(j) $D \to Kl\nu$	(l) $R_{\tau\pi}$	(m) R_{D_s}	combination
λ'^2_{11k}	-0.11 ± 0.08	0.14 ± 0.11		0.12 ± 0.15					-0.002 ± 0.056
λ'^2_{12k}	-0.47 ± 0.33				0.2 ± 2.1	-0.17 ± 2.56			-0.46 ± 0.32
λ'^2_{13k}	$-32. \pm 24.$								$-32. \pm 24.$
λ'^2_{1j1}				-0.22 ± 0.26					-0.22 ± 0.26
λ'^2_{1j2}					-4.3 ± 4.7				-4.3 ± 4.7
λ'^2_{1j3}					1.5 ± 0.8				1.5 ± 0.8
λ'^2_{21k}		-0.14 ± 0.11	0.71 ± 0.73				$-0.46 \pm 0.55^\dagger$		-0.12 ± 0.11
λ'^2_{22k}						-0.003 ± 2.6		5.1 ± 23.1	0.06 ± 2.60
λ'^2_{2j1}			-6.9 ± 5.1						-6.9 ± 5.1
λ'^2_{31k}							0.46 ± 0.55		0.46 ± 0.55
λ'^2_{32k}								-4.7 ± 19.9	-4.7 ± 19.9

Table 3: Combined results on λ^2 and λ'^2 from tree level processes; a factor of $10^{-2} \times (\tilde{m}/100)^2$ is implicit everywhere. (†) Not used in the combination (not independent).

2.1 Neutrinoless double β decay

The limit from neutrinoless double β decay [16] quoted in table 4 was obtained recently using $t_{1/2}(^{76}Ge) > 9.1 \times 10^{24}$ yr. The present experimental result is only very slightly better at $t_{1/2}(^{76}Ge) > 1.1 \times 10^{25}$ yr [17] ; we made no attempt to update the limit.

2.2 Neutrino masses

An approximate expression for a Majorana mass induced by self-energy type diagrams (see figure 6) is [18]:

$$\delta m_{\nu_i} \simeq \frac{\lambda_{ikk}^2 N_c}{16\pi^2} \frac{M_{SUSY} m_f^2}{m_{\tilde{f}}^2}.$$

assuming a sfermion mass matrix off-diagonal term $M_{SUSY} m_f$. A non zero λ allows a lepton-slepton loop, a non zero λ' allows a quark-squark loop.

Assuming in addition $M_{SUSY} = m_{\tilde{f}}$, the resulting limits in λ and λ' have been recomputed using the following limits, at 95%CL: $m_{\nu_e} < 15$ eV, $m_{\nu_\mu} < 0.17$ MeV, $m_{\nu_\tau} < 24$ MeV [5], and using $m_s = 100$ MeV, $m_b = 4.5$ GeV. They are displayed in table 4; they are a factor of about 2 more conservative than what Bhattacharyya quoted in [15] ($\lambda_{133} \leq 0.003$, $\lambda'_{122} \leq 0.02$ and $\lambda'_{133} \leq 7.10^{-4}$) because he used the optimistic limit $m_{\nu_e} < 5$ eV. The limits on λ and λ' extracted from the experimental limit on the ν_μ mass have not been quoted elsewhere, however at the moment no other process gives such a strict constraint on λ'_{233}.

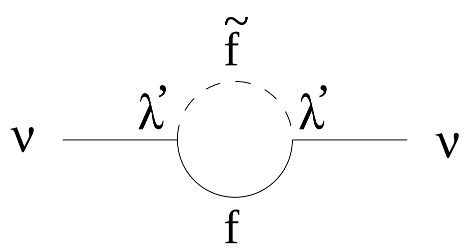

Figure 6: R_p violation induced self-energy diagrams

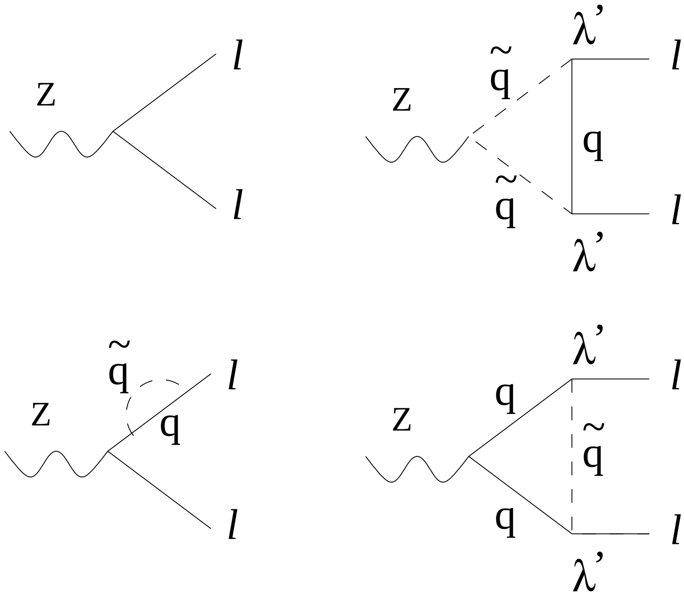

Figure 7: One loop R_p violating contributions to $Z \to l\bar{l}$.

2.3 $Z \to l\bar{l}$

The calculations necessary to extract limits on λ' from the precise measurement of $R_l = \Gamma_{had}(Z)/\Gamma_{ll}(Z)$ have been performed by Bhattacharyya et al. [3] and updated recently at the 1σ level [15, 19]. In table 4, we show our update at the 2σ level; the relevant diagrams are shown in figure 7.

2.4 Top decays

Just like other weak decays, top decays can be used to check the presence of a non zero λ' (see figure 8); we did not include them in section 1 only because top quark physics is still a very young field. One can either check lepton universality again, by comparing for instance $Br(t\bar{t} \to e + jets)$ to $Br(t\bar{t} \to \mu + jets)$, or directly compare $\sigma(t\bar{t})_{exp}$ to theoretical expectation $\sigma(t\bar{t})_{th}$. Both methods give about the same sensitivity on λ': $|\lambda'_{i3k}| < 0.41$ (first method), 0.48 (second method) at 95% CL, $i \neq 3$, for $m_{\tilde{l}} = 100$ GeV [4]. The hypothesis made in such a derivation are rather restrictive: $m_t > m_{\tilde{l}}$, $Br(\tilde{l} \to \tilde{\chi}^0 l) = 100\%$, $50 < m_{\tilde{l}} < 100$ GeV, $m_{\tilde{\chi}^0} > m_b$.
We have used the second method to recompute the limit with the latest ex-

Figure 8: Top decays.

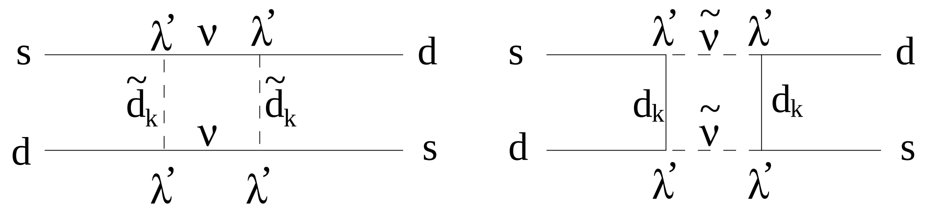

Figure 9: R_p violating contributions to $K^0\bar{K}^0$ mixing.

perimental and theoretical results:
$\sigma(t\bar{t})_{D0} = 5.5 \pm 1.8$ pb at $m_t = 173.3$ GeV [20], which transforms to $\sigma(t\bar{t})_{D0} = 5.2 \pm 1.7$ pb at $m_t = 175$ GeV; $\sigma(t\bar{t})_{CDF} = 7.6^{+1.8}_{-1.5}$ pb at $m_t = 175$ GeV [21]; $\sigma(t\bar{t})_{Berger} = 5.52^{+0.07}_{-0.42}$ pb [22], $\sigma(t\bar{t})_{Catani} = 4.75^{+0.73}_{-0.62}$ pb [23] at $m_t = 175$ GeV.
The limit on λ' depends of course on wether one uses Berger et al. or Catani et al. predictions. To be conservative, we use the latter, which is in bigger disagreement with the experimental result. Combining $D0$ and CDF measurements: $\sigma(t\bar{t})_{exp} = 6.55 \pm 1.1$ pb at $m_t = 175$ GeV, we get $|\lambda'_{i3k}| <^{0.49(1\sigma)}_{0.55(2\sigma)}$, $i \neq 3$, $k \neq 3$ for $m_{\tilde{l}} = 100$ GeV.
This is not better than 1996 limit; as top quark physics is a field evolving very fast, both experimental and theoretical numbers are still in flux, and the limit on $|\lambda'_{i3k}|$ will benefit from improvement on both sides.

2.5 Mixing and FCNC processes

There are R_p violating contributions to $K^0\bar{K}^0$, $B^0\bar{B}^0$ mixing through the box diagrams shown in figure 9, and also to flavour changing neutral current (FCNC) decays $K \to \pi\nu\bar{\nu}$ and $b \to s\nu\bar{\nu}$ decays. Limits on λ' have been derived [4, 24] under the assumption that the absolute mixing occurs only in the down-type quarks sector, not in the up-type quarks sector; these limits

	(n) neutrinoless $\beta\beta$ (90%CL)	(o) $m(\nu)$ (95%CL)	(p) R_l (2σ)	(q) top decays (2σ)
λ_{122}		$0.1\sqrt{m_{\tilde{\mu}}/100}$		
λ_{133}		$6.10^{-3}\sqrt{m_{\tilde{\tau}}/100}$		
λ_{233}		$0.65\sqrt{m_{\tilde{\tau}}/100}$		
λ'_{111}	$5.2\times 10^{-4}\times f(\tilde{m})$			
λ'_{122}		$0.06\sqrt{m_{\tilde{s}}/100}$		
λ'_{133}		$1.4\,10^{-3}\sqrt{m_{\tilde{b}}/100}$		
λ'_{233}		$0.15\sqrt{m_{\tilde{b}}/100}$		
λ'_{333}		$1.8\sqrt{m_{\tilde{b}}/100}$		
λ'_{i3k}			$i=1$: 0.47 $i=2$: 0.45 $i=3$: 0.58	$i\neq 3$: $k\neq 3$: 0.55 $[1.13\times g(\tilde{m})]$ $k=3$: 0.41 $[0.84\times g(\tilde{m})]^{(*)}$

Table 4: Limits on λ and λ' coming from loop, box,... processes. A factor of $\tilde{m}/100$ is implicit for process (p); $f(\tilde{m}) = (m_{\tilde{e}}/100)^2 \times (m_{\tilde{\chi}^0}/100)^{1/2}$, $g(\tilde{m}) = (3-(m_{\tilde{l}}/100)^2)^{-1}$; $^{(*)}$ limit at 95% CL.

	(r) $K^0\bar{K}^0$ mix.	(s) $B^0\bar{B}^0$ mix.	(t) $K\to\pi\nu\nu$ (90%CL)	(u) $b\to s\nu\nu$ (90%CL)	(v) $D^0\bar{D}^0$ mix. (90%CL)
λ'_{i1k}	$0.09[0.11\times f(\tilde{m})]$	$0.92[1.1\times f(\tilde{m})]$	0.012		$0.20[0.24\times g(\tilde{m})]$
λ'_{i2k}	$0.09[0.11\times f(\tilde{m})]$		0.012	0.19	$0.20[0.24\times g(\tilde{m})]$
λ'_{i3k}		$0.92[1.1\times f(\tilde{m})]$	0.52	0.19	

Table 5: Basis dependent limits on λ'. A factor of $\tilde{m}/100$ is implicit unless otherwise stated; $f(\tilde{m}) = [(100/m_{\tilde{\nu}})^2 + (100/m_{\tilde{d}})^2]^{-1/4}$, $g(\tilde{m}) = [(100/m_{\tilde{l}})^2 + (100/m_{\tilde{d}})^2]^{-1/4}$.

are basis dependent, they vanish if the opposite assumption is made, in which case one can then obtain a bound from $D^0\bar{D}^0$ mixing [4, 25]. They are shown in table 5. Because these limits are not as reliable as the other ones, we do not update them, although they must have improved since they correspond to the experimental status of 1995.

For instance, concerning the mixings, λ' decreases with Δm ($m_{K_L} - m_{K_S}$ or $m_{B_H} - m_{B_L}$). Now, Δm_K has moved from (3.510 ± 0.018) to (3.495 ± 0.012) 10^{-12} MeV and Δm_B has varied from (3.36 ± 0.39) to (3.186 ± 0.171) 10^{-10} MeV [5], therefore in both cases, both the central value and the uncertainty have decreased, giving significantly smaller upper limits. On the other hand, box diagrams are order λ'^4 diagrams, so the limits obtained on λ' does not vary as fast as those on Δm.
We have also checked, incidentally, the validity of one of the hypothesis used in the $B^0\bar{B}^0$ derivation, namely that only the top quark contribution should be taken into account in the SM contribution, and that the u and c could be neglected. Indeed, the c quark contribution becomes of the same order as the R_p violating one for $\lambda' \simeq 0.05$, which is about one order of magnitude smaller than today's limit.

Concerning the two FCNC processes $K \to \pi\nu\bar{\nu}$ and $b \to s\nu\bar{\nu}$, again the limits on λ' are varying very slowly because in the assumption that the SM does not contribute, the dependance in the branching ratios is again as λ'^4. On the other hand, in the case of $K \to \pi\nu\bar{\nu}$ for instance, both measurement and SM expectation have considerably evolved:

$Br(K^+ \to \pi^+\nu\bar{\nu})$	SM	exp.
1995	$1.6\ 10^{-11}$ [26]	$< 5.2\ 10^{-9}$ (90% CL) [4]
today	$(8.0 \pm 1.5)10^{-11}$ [27]	$(4.2^{+9.7}_{-3.5})10^{-10}$ [28]

When Agashe et al. wrote their paper, there was a factor of more than 300 between the experimental limit and the theoretical expectation; this factor is now of only about 5 if one uses the central value of the branching ratio measurement, and 20 comparing to the upper bound at 90% CL. The measurement and the prediction are now compatible, so that it seems to us that neglecting the SM contribution is not a valid assumption anymore: one should redo the calculation taking into account the SM contribution.

ijk	λ_{ijk} limit at 2σ	ijk	λ'_{ijk} limit at 2σ	ijk	λ'_{ijk} limit at 2σ	ijk	λ'_{ijk} limit at 2σ
121	0.05 (a)	111	5.2×10^{-4} (n)	211	0.06 (f)	311	0.12 (l)
122	0.05 (a)	112	0.02 (a)	212	0.06 (f)	312	0.12 (l)
123	0.05 (a)	113	0.02 (a)	213	0.06 (f)	313	0.12 (l)
131	0.07 (b)	121	0.04 (a,h)	221	0.18 (g,j)	321	0.52 (m)
132	0.07 (b)	122	0.04 (a)	222	0.18 (j)	322	0.52 (m)
133	0.006 (o)	123	0.04 (a)	223	0.18 (j)	323	0.52 (m)
231	0.07 (b,c)	131	0.04 (h)	231	0.18 (g)	331	0.58 (p)
232	0.07 (b,c)	132	0.28 (i)	232	0.45 (p)	332	0.58 (p)
233	0.07 (b,c)	133	1.4×10^{-3} (o)	233	0.15 (o)	333	0.58 (p)

Table 6: Summary of the 2σ limits on λ and λ' for $\tilde{m} = 100$ GeV; the letter between brackets indicates the process from which the limit is extracted according to tables 1 to 4. Limits from process (n) and (o) are at 90% and 95% CL respectively.

On the other hand, $b \to s\gamma$ decays can also provide interesting constraints: CLEO has measured $Br^{exp}(B \to X_s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ [29] which is well compatible with the SM expectation $Br^{SM}(B \to X_s\gamma) = (3.25 \pm 0.30 \pm 0.40) \times 10^{-4}$ [30]. However, these results are interpreted only in terms of limits on $\lambda'\lambda'$ products [31].

Conclusions

All the results have changed with new data though there has not been dramatic changes. Due to the method used, limits can weaken when experimental precision increases, or when better theoretical SM expectations are available. Therefore one should consider as many processes as possible.

Still, not all of the 9 λ and 45 λ' are constrained, see a selection of the most stringent limits (optimistic method) as of today in table 6. In selecting these limits, we do not take into account those being basis dependent (processes (r) to (v)).

The most reliable limits on λ, λ' are obtained from processes for which both SM and R_p violating graphs are tree level diagrams.

Heavy flavour decays are extensively used to set limits on both λ and λ', especially τ decays, but also D and top decays, and possibly B decays. Many limits would obviously benefit from the experimental output of a possible τ-charm factory, and probably from a B-factory as well.

Acknowledgements

We wish to thank C. Bérat for very helpful discussions and for useful cross-checks of our calculations, as well as S. Katsanevas, C. Savoy and D. Perret-Gallix for interesting suggestions to improve the completeness of this review.

References

[1] V. Barger et al., Phys. Rev. **D40** (1989) 2987.

[2] G. Bhattacharyya and D. Choudhury, Mod. Phys. Lett. **A10** (1995) 1699.

[3] G. Bhattacharyya, J. Ellis and K. Sridhar, Mod. Phys. Lett. **A10** (1995) 1583.

[4] K. Agashe and M. Graesser, Phys. Rev. **D54** (1996) 4445.

[5] R.M. Barnett et al., Phys. Rev. **D54** (1996) 1, and 1997 off-year partial update for the 1998 edition (URL: `http::///pdg.lbl.gov`).

[6] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavour Group, CERN-PPE/97-154

[7] W.J. Marciano, Nucl. Phys. **B** (Proc. Suppl.) **40** (1995) 3.

[8] W.J. Marciano and A. Sirlin, Phys. Rev. Lett. **71** (1993) 3629.

[9] D. Decker and M. Finkemeier, Phys. Lett. **B 334** (1994) 199.

[10] G. Altarelli et al., Nucl. Phys. **B 506** (1997) 29.

[11] J.Z. Bai et al. (BES colaboration), Phys. Rev. Lett. **74** (1995) 4599.

[12] K.S. McFarland et al. (CCFR, E744 and E770 collaborations), Eur. Phys. J. **C1** (1998) 509.

[13] P. Vilain et al., Phys. Lett. **B 335** (1994) 246.

[14] V. Barger et al., Phys. Rev. **D57** (1998) 3833.

[15] G. Bhattacharyya, IFUP-TH 43/97 (hep-ph/9709395).

[16] A. Faessler et al., Phys. Rev. Lett. **78** (1997) 183.

[17] M. Günther et al., Phys. Rev. **D55** (1997) 54;
L. Baudis et al., Phys. Lett. **B407** (1997) 219.

[18] R. Barbieri et al., Phys. Lett. **B 252** (1990) 251;
R.Adhikari and G.Omanovic, prep. IMSC/98/02/07 (hep-ph/9802390);
R. Mohapatra, Phys. Rev. **D34** (1986) 3457.

[19] J. Ellis et al., Phys. Lett. **B408** (1997) 252.

[20] S. Abachi et al. ($D0$ collaboration), Phys. Rev. Lett. **79** (1997) 1203.

[21] F. Abe et al. (CDF collaboration), Phys. Rev. Lett. **80** (1998) 2773.

[22] E.L. Berger and H. Contopanagos, Phys. Rev. **D54** (1996) 3085.

[23] S. Catani et al., Phys. Lett. **B 378** (1996) 329.

[24] Y. Grossman, Z. Ligeti and E. Nardi, Nucl. Phys. **B465** (1996) 369.

[25] H. Dreiner, to be published in 'Perspectives on Supersymmetry', Ed. by G.L. Kane, World Scientific (hep-ph/9707435).

[26] T. Inami and C.S. Lim, Prog. Theor. Phys. **65** (1981) 297.

[27] F. Bossi et al., prep. LNF-98/004(P) (hep-ph/9802345).

[28] S. Adler et al., Phys. Rev. Lett. **79** (1997) 2204.

[29] M.S. Alam et al. (CLEO collaboration), Phys. Rev. Lett. **74** (1995) 2885.

[30] J.L. Hewett, prep. SLAC-PUB-7774 (hep-ph/9803370).

[31] B. de Carlos and P.L. White, Phys. Rev. **D55** (1997) 4222.